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RAIL DAMAGE IN A SOLID ARMATURE RAIL GUN

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Two types of rail guns are currently under investigation to meet Army tactical missions. Plasma arc drive rail guns operate by forming a high temperature plasma behind the projectile using a thin metal fuze. These systems achieve the highest projectile velocities (~ 12 km/sec), since the driving force includes a substantial plasma pressure as well as the electromagnetic or Lorentz force. Unfortunately, severe rail damage occurs primarily

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from the intense temperatures generated by the plasma arc and the wiping motion of the armature itself. This severe rail damage is not compatible with Army tactical ~~missions~~ requiring multi-shot applications. The plasma armature gun will not be discussed in this report.

The solid armature gun replaces the plasma armature with a conducting metal armature. Since the plasma arcing is reduced or eliminated, the projectiles are accelerated mainly by the Lorentz force. Thus, solid armature rail guns operate at lower projectile velocities. The important tradeoff is that there is a substantial reduction in rail damage for metal armature projectiles.

Several factors limit projectile velocities in the metal armature rail guns. The most obvious is the elimination of the plasma force. However, a more subtle limit is the speed at which the commutation process can take place. Although the latter limit is still not well understood, experimental evidence indicates a commutation limit may occur near 6 to 7 km/sec. This velocity limit is still attractive for Army tactical missions for rail guns.

The actual rail damage occurring with two types of metal armatures, wire brush contactors and monolithic metal contactors, and new developments in barrel technology, such as superconducting augmentation, are presented in this report.

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INTRODUCTION

Rail gun technology is rapidly being developed both for the Strategic Defense Program (SDI) and for tactical Army applications. In general, rail gun technology will be required whenever projectile velocity or minimum projectile time of flight demands exceed the capabilities of normal chemical propellants. Under present chemical launch capabilities, muzzle velocities in excess of 2 km/sec will require some sort of an electromagnetic (EM) system.

The two types of armature drives, plasma and solid types, characterize present rail gun development. Both types have their advantages and disadvantages which will dictate the type used by system requirements.

The plasma armature rail gun adds a plasma push force to the normal Lorentz magnetic force to obtain extremely high projectile velocities (> 10 km/sec) in small mass systems. The main disadvantage of the plasma drives is the severe rail damage caused by the high temperature plasma arcs which limits barrel lifetimes to a few launches at most. However, single shot missions for very high velocity missions will probably use plasma armatures.

Since Army tactical missions require multi-shot capability, this report concentrates on the solid armature type propulsion in which rail damage is significantly reduced.

In the first section, a brief description of rail circuits is presented to suggest some of the static and dynamic responses which may occur in these systems.

The second section presents actual launch results that illustrate some of the unusual loading conditions which can occur in these systems, either intentionally or accidentally, due to the electromagnetic origin of the propulsion force.

In the final section, we describe preliminary rail damage data obtained from two different metallic armatures to illustrate that the type and extent of rail damage is dependent not only on launch conditions, but on armature materials as well.

RAIL GUN CIRCUITS

Figure 1 is a schematic of the basic rail gun circuit. Electrical energy is supplied in a suitable pulse shape to the rail gun circuit. The resulting current waveform I(t) will produce the propelling Lorentz force F_{SRG}

$$F_{SRG}(t) = \tfrac{1}{2} * L' \, I^2(t) \qquad (1)$$

where L' is the magnetic self-inductance gradient of the rails. Although a constant high current has the highest launch velocity/energy input efficiency, actual rail guns are generally powered by a capacitive-like discharge from an energy source.

After closing switch S, the electrical energy stored in the capacitor ($\tfrac{1}{2}$ QC^2) is converted to current energy in the inductor ($\tfrac{1}{2}$ LI^2). This is accomplished before the projectile P moves. At this point, the crowbar switch CS is normally closed, converting the electrical system from an oscillatory LCR circuit to a decaying LR rail gun circuit. (In the next section, we discuss the rail gun behavior when the crowbar is not used.)

In an earlier presentation (ref 1) we showed that when the current decays to zero before the projectile reaches the end of the rails, the muzzle velocity v_F will be

$$v_F \cong \frac{L_O E_O}{2mR} \qquad (2)$$

[1]C. G. Homan, C. E. Cummings, C. M. Fowler, and M. L. Hodgdon, "Superconducting Augmented Rail Gun (SARG) Development," presented at the Fourth International Conference on Megagauss Magnetic Field Generation, Santa Fe, NM, 14-17 July 1986.

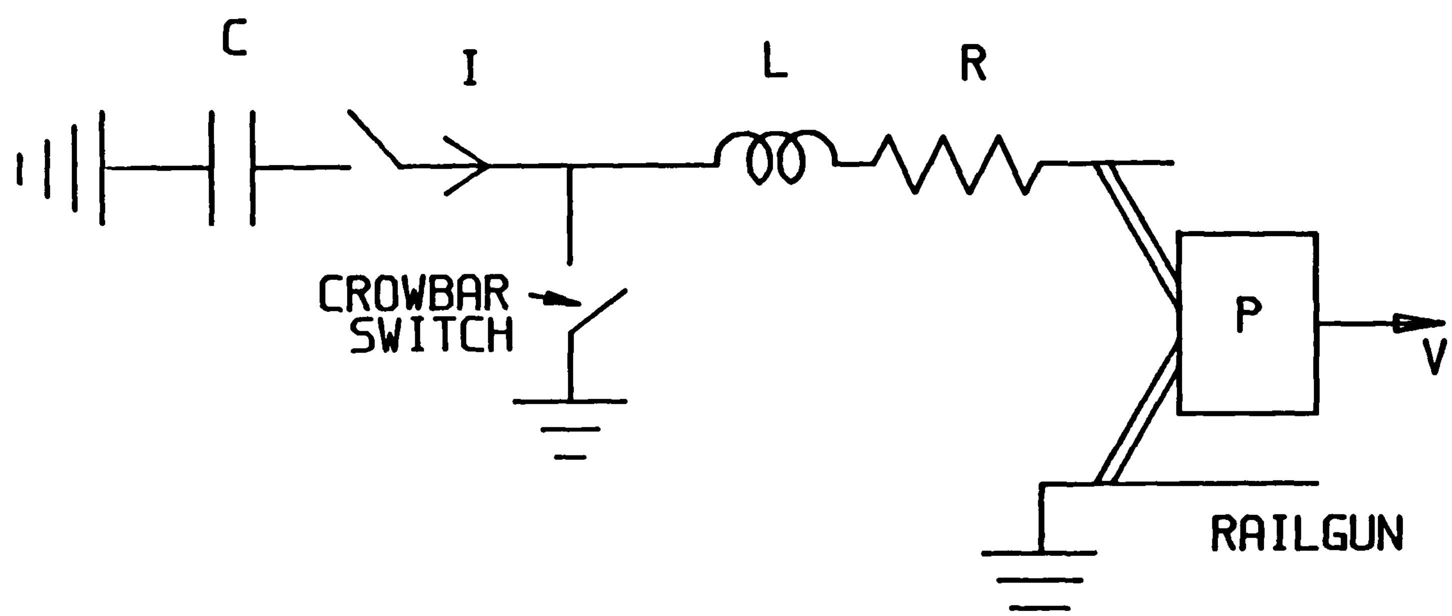

Figure 1. Schematic of the rail gun circuit. C - capacitance; L - inductance; R - lumped circuit resistance; and P - projectile moving with V - velocity.

where E_0 is the energy stored in the capacitor bank, m is the projectile mass, and R is the mean circuit resistance during launch. This formula was derived assuming frictional losses are negligible and has been shown to be in fairly good agreement with experimental data for low velocity launches (ref 1). Loss terms introduced at higher velocities, such as the resonance losses described by Simkins in Reference 2, may lead to significant correction terms in these formulae, since in general, the rail gun system will be more compliant than a normal gun system.

The simple rail gun described above is not a very efficient system, since any magnetic field energy stored in the rail fields at the end of launch must be dissipated. It is possible to show, from general energy considerations, that an ideal rail gun, operating at constant current, equipartitions the energy extracted from the power source into magnetic energy and projectile work, and therefore the maximum efficiency of such a system is 50 percent. Real rail guns operating at nearly constant current dissipate some of the projectile work into Joule heating, friction, etc., so that actual launch efficiencies are about 10 percent.

In an effort to increase barrel efficiency, Benet Laboratories developed the concept of superconducting augmentation. Figure 2 shows schematically a superconducting augmentation coil operating in the persistent mode magnetically coupled to the rail coil by the mutual inductance M

$$M = k \sqrt{LL_s} \tag{3}$$

[1]C. G. Homan, C. E. Cummings, C. M. Fowler, and M. L. Hodgdon, "Superconducting Augmented Rail Gun (SARG) Development," presented at the Fourth International Conference on Megagauss Magnetic Field Generation, Santa Fe, NM, 14-17 July 1986.

[2]T. E. Simkins, "Resonance of Flexural Waves in Gun Tubes," Proceedings of the Fifth U.S. Army Gun Dynamics Symposium, ARCCB-TR-87023, Benet Laboratories, Watervliet, NY, 23-25 September 1987, pp. 64-78.

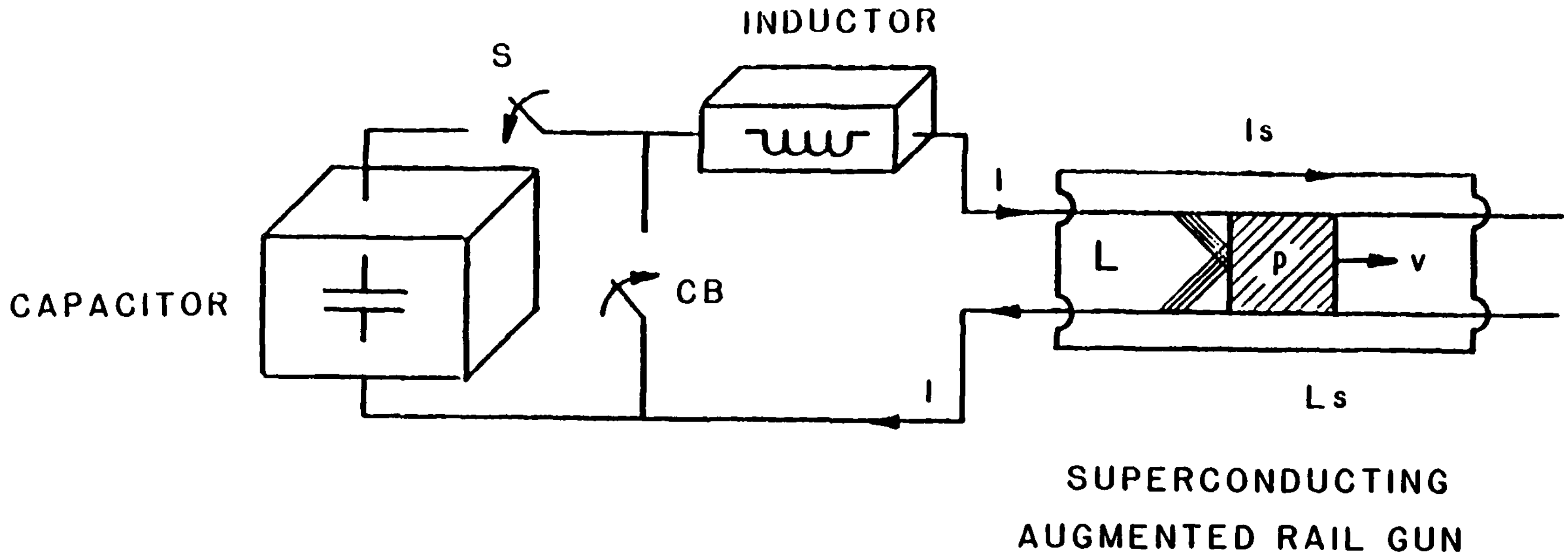

Figure 2. Schematic of the superconducting augmented rail gun circuit.

where L and L_s are the self-inductance of the rail coil and supercoil, respectively, and k is the coupling constant whose positive value can approach unity. Both L and k are dependent on projectile position. The superconducting coil recovers some of the magnetic field energy normally lost at the end of launch and augments the armature force as shown below.

In the development of the equations that follow, it is important to note that these equations are peculiar to a rail gun with a superconducting augmentation coil, since the superconducting property of flux trapping was used in their derivation. A normally conducting augmentation coil, which cannot be placed in a persistent mode, will exhibit the same efficiencies as an unaugmented system. This latter fact can be shown quite generally for any system of linear normally conducting circuits.

We have shown that the armature force F(x) for a SARG system is (ref 3)

$$F(x) = \tfrac{1}{2} L'I^2 + I\, I_{so}M' - xI^2M'^2/L_s \tag{4}$$

where the current I varies as

$$I = \frac{I_o - xI_{so}(M'/L_o)}{1 + x(L'/L_o) - x^2(M'^2/L_oL_s)} \tag{5}$$

and I_{so} is the initial supercurrent, L_o is the pulse shaping inductance, and the distance x is measured along the rails.

Now the point in presenting all this theory is that although these equations give reasonably good results for projectile velocity, barrel launch efficiency, etc., they are totally inadequate for the evaluation of barrel deformation and dynamics. The reason for this is that implicit in these calculations is the assumption that the rail current has fully penetrated the rails and is uniform. In fact, at reasonable velocities, the current sheet may be

[3] C. G. Homan and W. Scholz, "Evaluation of Superconducting Augmentation on Rail Gun Systems," IEEE Transactions on Magnetics, Vol. MAG-20, 1984, p. 366.

limited to the surface by the skin effect and is nonuniform along the barrel as suggested in Figure 3. It is obvious that a systematic evaluation of barrel dynamics is not a trivial process, but requires the solution of the electrodynamics of the system as well. At the present time, computer codes have been developed to try to evaluate barrel dynamics, however, no closed form solutions have been developed to date.

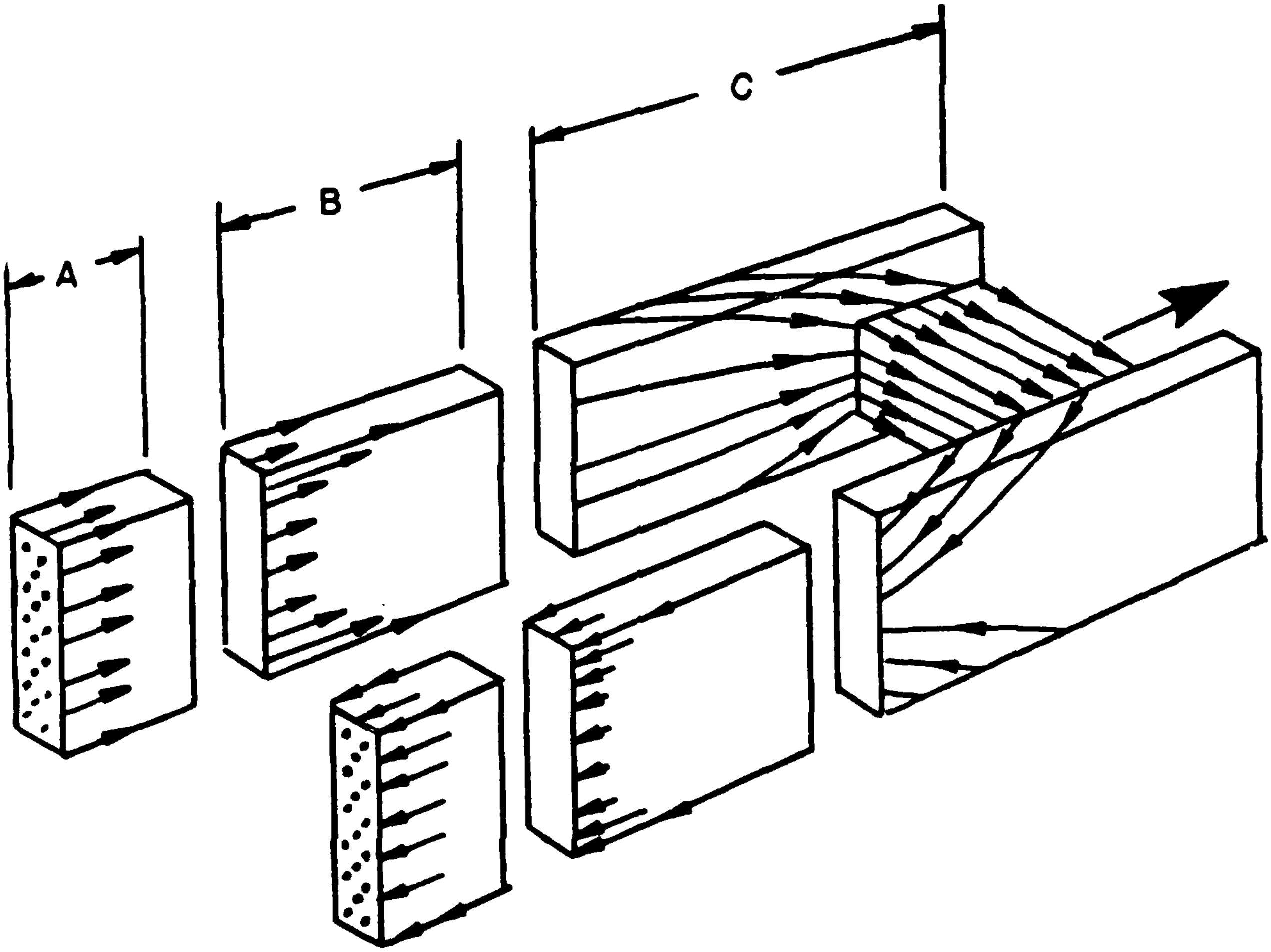

Figure 3. Distribution of current in a rail gun. Region A indicates full current penetration changing to symmetric surface currents in the mid region B, and finally, to the asymmetric surface distributions at the armature.

ACTUAL RAIL GUN PERFORMANCE AND ANALYSIS

In this section we present the analysis used to evaluate the performance of a series of launches of a small rail gun at Los Alamos (ref 1). In particular, we chose special launch conditions to illustrate dynamic behavior which is peculiar to the electromechanical nature of rail gun systems.

Consider the circuit of Figure 1. If the crowbar switch is not closed for whatever reason, then the circuit remains a classical damped electromechanical oscillator. If all the circuit elements (rails, inductors, etc.) are rigid, then the system can be analyzed as an electrical oscillator obtaining the current

$$I(t) = -Q/LC_w * e^{-bt} * \sin wt \qquad (6)$$

where $w = \sqrt{w_o^2 - b^2}$, $w_o^2 = 1/LC$, and $b = R/2L$. Interestingly, if the current decays to zero before the projectile exits the gun, we recover Eq. (2), i.e.,

$$v_F \cong \frac{LE_o}{2mR} \qquad (7)$$

Thus, for low velocity systems, a suitable EM design could eliminate this complication of a crowbar switch, however, subjecting the mechanical system to an oscillatory driving force.

In Figure 4 we show the actual current response of an uncrowbarred rail gun, in which the mechanical behavior manifests itself through the temporal variation of w_o and b. Also shown are the calculated currents from Eq. (6) using constant mean values of $\bar{w}_o$ and $\bar{b}$. In this system, these variations were found to be primarily due to the mechanical oscillation of the pulse shaping coil.

[1] C. G. Homan, C. E. Cummings, C. M. Fowler, and M. L. Hodgdon, "Superconducting Augmented Rail Gun (SARG) Development," presented at the Fourth International Conference on Megagauss Magnetic Field Generation," Santa Fe, NM, 14-17 July 1986.

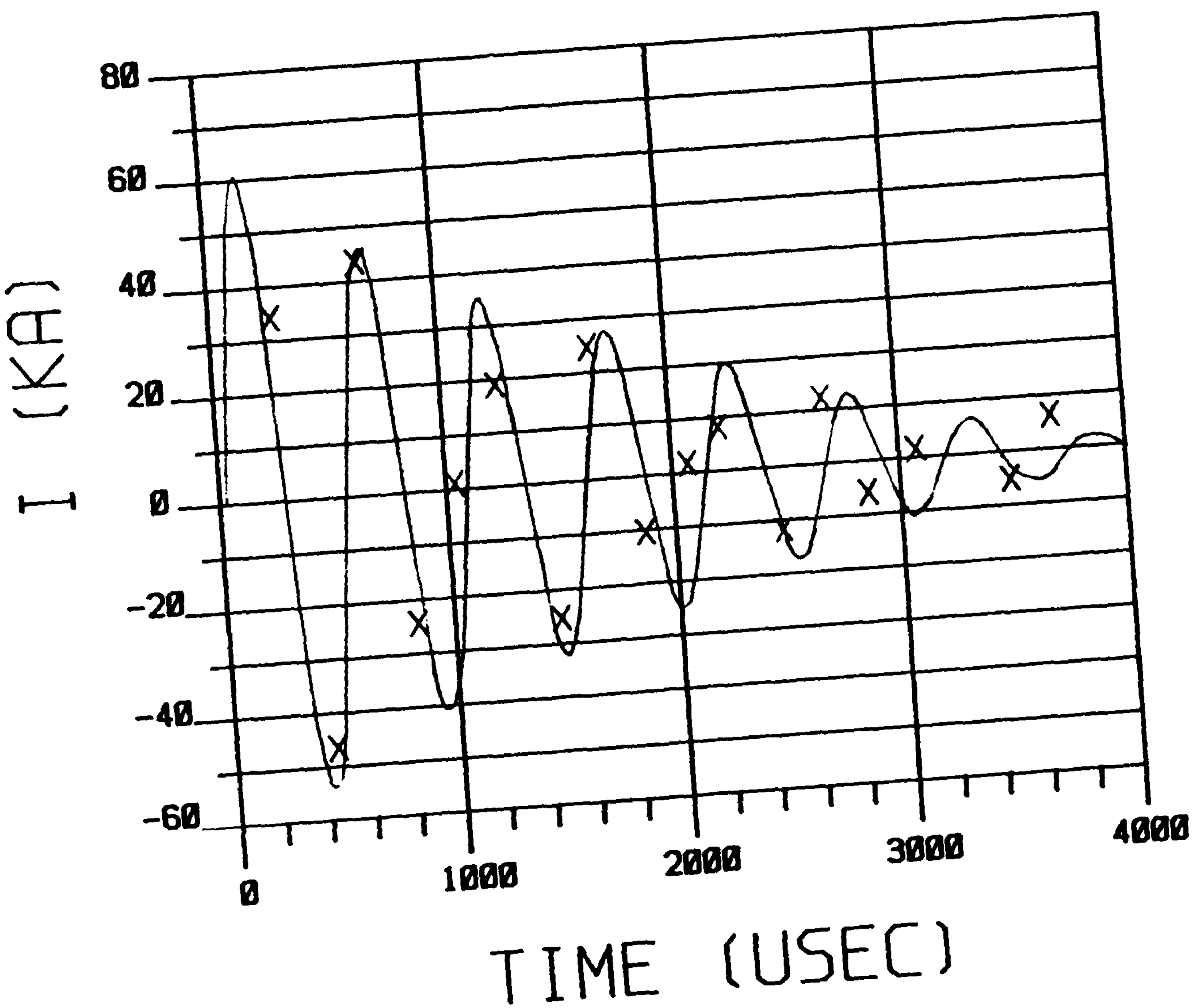

Figure 4. Current oscillations in non-crowbarred rail gun.

RAIL DAMAGE

In this final section, we describe the typical damage solid armature rail guns experience during launch. The type of rail damage can be characterized principally by the materials present and, to a lesser degree, by launching conditions. On the other hand, the extent of damage is principally controlled by firing conditions. We will focus on the types of rail damage herein, relating when necessary to effects of firing conditions on the type of damage.

Before we proceed, we can make some general comments about the extent of rail damage due to launch conditions. Two major factors in the extent of damage are projectile velocity and armature condition. Since most rail damage is due to surface heating, it is obvious that a nonarcing solid armature will have less extensive rail damage than a plasma armature. Likewise, a fast moving armature is less damaging that a slow one. For these reasons, solid armature rail guns with projectile injection will probably be used for multi-shot tactical weapons.

Two different armature designs were tested in the Los Alamos launches. In this 3/8-inch square bore rail gun powered by a 15 kJoule capacitor bank through a 5 microhenry pulse shaping coil, projectiles were either Lexan rectangular parallelopipeds having an armature of niobium wires imbedded in a copper matrix or monolithic aluminum projectiles of the same shape.

The Lexan projectile armatures were made by etching the copper matrix material from the niobium wire of a superconducting cable, resulting in rather stiff, short bristle niobium brushes contacting the copper rails.

The aluminum projectiles had narrow contactor leaves machined into the rear of the projectile to concentrate the current and to be deformable by a Lexan plug to insure contact with the rails.

Both armatures suffered severe metallurgical damage characterized by melting, however, since armatures are expendable in a rail gun system, we will concentrate on the type of damage to the rails caused by the different armatures.

As mentioned earlier, the Lexan projectiles' niobium copper armatures experienced severe plasma arcing as witnessed by performance and rail damage. The as-received rail material was a high conductivity copper bar containing traces of zinc, aluminum, zirconium, titanium, cadmium, iron, magnesium, and cadmium with a hardness of Rockwell B53. Careful metallographic examination after each launch revealed three basic elements to the severe erosion which occurred at the initial projectile position. The primary modification was a metallurgically bonded columnar layered structure characteristic of melting and solidification. In addition, weld pools suggesting eddy current flow patterns and a spongy surface layer of copper oxide were observed. EDAX analysis of these areas detected elemental niobium and carbon in abundance, however, no compounds or second phases of niobium or copper were found with the exception of the surface oxides. This is not unexpected since the phase diagram indicates almost complete miscibility of the two elements. Figure 5 shows the typical damage obtained at the projectile initial position. Of course, farther down bore, much less damage occurs as the projectile accelerates. In the high velocity regions, the principal damage is a heavy surface coating of soot (CuO) caused by the plasma arc.

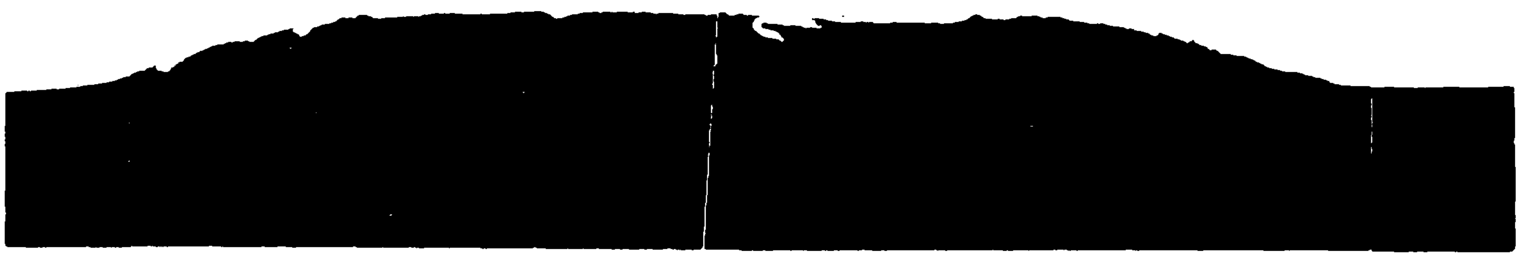

Figure 5a. Rail damage at origin of launch for niobium brush armature (20X).

Figure 5b. Photomicrograph showing columnar recrystallization typical of niobium armature launch (200X).

When the aluminum projectiles were used, hardly any arcing occurred and less severe rail damage was seen at the projectile origin position. However, the character of the damage was quite different. Careful metallography revealed an acicular type microstructure as shown in Figure 6. From preliminary EDAX analysis, at least two different compounds of aluminum copper were identified in this region. Examination of the aluminum copper phase diagram revealed several compounds (bronzes) for this system which explains the complex metallurgical behavior occurring in this zone.

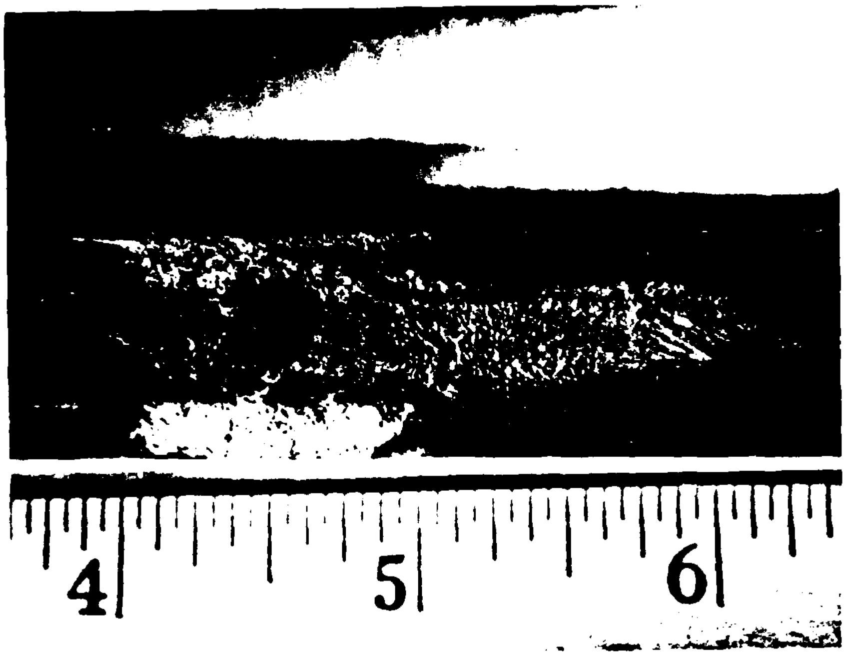

Figure 6a. Rail surface damage for solid aluminum armature.

Figure 6b. Photomicrograph of acicular recrystallization zone for solid aluminum armatures. Several different aluminum-copper bronzes were identified (1000X).

CONCLUSIONS

The purpose of this report was to present some of the new problems that can occur in rail guns and that may be of some interest to the gun dynamics community.

The uncrowbarred rail gun was presented in some detail to illustrate the rail gun as an electromechanical system, which is normally damped, but can be excited in a resonant condition.

Finally, a brief glimpse of rail damage as being related to the conditions of launch as well as the materials involved, was presented to introduce the gun dynamics community to these important factors which may play a strong role in any analysis of rail gun behavior.

REFERENCES

1. C. G. Homan, C. E. Cummings, C. M. Fowler, and M. L. Hodgdon, "Superconducting Augmented Rail Gun (SARG) Development," presented at the Fourth International Conference on Megagauss Magnetic Field Generation, Sante Fe, NM, 14-17 July 1986.

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3. C. G. Homan and W. Scholz, "Evaluation of Superconducting Augmentation on Rail Gun Systems," IEEE Transactions on Magnetics, Vol. MAG-20, 1984, p. 366.

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